Appendix : Photon Sail History, Engineering, and Mission Analysis

This Appendix summarizes the results of a Teledyne Brown Engineering, Inc. report to the In-Space propulsion research group of the NASA Marshall Space Flight Center (MSFC) that was authored by Taylor et al. in 2003. The subject of this report is the technological maturity, readiness, and capability of the photon solar sail to support space-exploration missions.

Technological maturity for solar photon sail concepts is extremely high high for rectangular (or square) solar sail configurations due to the historical development of the rectangular design by the NASA Jet Propulsion Laboratory (JPL). L'Garde Inc., ILC Dover Inc., DLR, and many other corporations and agencies. However, future missions and mission analysis may prove that the rectangular sail design is not the best architecture for achieving mission goals. Due to the historical focus on rectangular solar sail spacecraft designs, the maturity of other architectures such as hoop-supported disks, multiple small disk arrays, parachute sails, heliogyro sails, perforated sails, multiple vane sails (such as the Planetary Society's Cosmos 1), inflated pillow sails, etc., have not reached a high level of technological readiness. (Some sail architectures are shown in Fig. A.1.) The possibilities of different sail architectures and some possible mission concepts are discussed in this Appendix.

A.1 Brief History of Solar Photon Sailing

The basic theory underlying solar sailing was first published in 1873 by the Scottish physicist James Clerk Maxwell. Maxwell demonstrated that incident electromagnetic radiation, such as a beam of light, should exert a pressure on a surface. As described by McInnes in 1999, Maxwell's theory may have inspired an 1889 science-fiction story by the

French authors Faure and Graffigny about mirror-propelled spacecraft.

Maxwell's theoretical prediction of radiation pressure was confirmed experimentally in 1900 by the Russian physicist Peter Lebedew. In 1905, Albert Einstein quantized Maxwell's theory showing that light particles (called quanta or photons) could indeed possess momentum. The transfer of this momentum to a reflective surface is the basis of solar-sail propulsion.

Little further progress was made until 1921, when Konstantin Tsilkovsky, the Russian "father" of astronautics and rocketry, published *Extension of Man into Outer Space*, in which he discussed photonic spacecraft propulsion. His colleague Friedrickh Tsander was inspired by this work to publish similar theories in 1924. Tsander suggested that by "using tremendous mirrors of very thin sheets" and "using the pressure of sunlight" cosmic velocities could be achieved.

In 1951, an American aeronautical engineer named Carl Wiley published a story in *Astounding Science Fiction* in which solar sails are used for orbit raising. The first technical journal publication about solar sailing was in 1958 by Richard Garwin. This work was followed by Tsu's classic "Interplanetary Travel by Solar Sail" in 1959. Although Arthut C. Clarke published a 1963 science-fiction story about a solar-sail race, the 1960's were dominated by the space race between the US and the USSR and the major technical focus was on rocketry.

NASA funded Battelle laboratories in 1973 to study various solar sailing concepts. Jerome L. Wright, who would later author a text on the subject, directed the project. In 1976, as discussed by McInnes, a formal proposal was submitted to NASA directors suggesting that a solar sail could be used for a rendezvous mission with Halley's comet. The program, managed by Louis Friedman, was dropped in 1977 and a solar-electric propulsion system was chosen instead. The 1986 US Halley rendezvous mission was later canceled.

After its inception in 1979, the World Space Foundation (WSF) along with the Union pour la Promotion de la Propulsion Photonique (U3P) proposed a solar sail race to the Moon. A third solar sail advocacy group, the Solar Sail Union of Japan (SSUJ) was formed in 1982. Possibly because of the growing influence of advocacy groups, more serious work on solar-sail theory, design, and construction was undertaken during the 1980's than before. This pioneering research is discussed by Forward (1984), Mallove and Matloff (1989), and McInnes (1999). In 1986, Poyakhova published the first modern monograph devoted to solar sailing. This was followed by a semi-popular treatment authored by Louis Friedman, a co-founder of The Planetary Society. Much of Mallove and Matloff's *The Starflight Handbook* (1989) is devoted to lightsails. Another solar-sail monograph was authored by Jerome L. Wright in 1992. Also in 1992, the US Columbus Quincentennial Jubilee commission formed and attempted (unsuccessfully) to revive the idea of a solar-sail race in space. In 1994, D. M. Souza published a semi-popular treatment of solar sails. The most recent monograph devoted to this subject was authored by Colin McInnes in 1989.

Significant experimental development began in the 1990's. A Russian Progress rocket deployed a 20-meter diameter spinning reflector near space station Mir in 1993. A 14-meter diameter inflatable radio-frequency reflector was deployed in 1996 during space shuttle mission STS-77. Both of these experiments successfully demonstrated the deployment in space of a large, gossmer structure.

During 1997-1999, Geoffrey Landis of Ohio Aerospace Institute conducted NASA-funded research to develop solar and laser photon-sail concepts.During this time period, another NASA effort called the Solar Thermal Upper Stage Program was funded to design and construct a large, inflatable optic for space applications. This inflatable optic was tested at the University of Alabama in Huntsville and the NASA Marshall Space Flight Center in 1997-1998, as discussed by D. A. Gregory.

Presently, work is continuing towards a deployable solar-sail technology demonstration. Many engineers and scientists continue to investigate the various aspects and possibilities of solar sailing. Many worldwide websites are devoted to solar sailing, including:

http://www.uges.caltech.edu/~diedrich/solarsails/

http://www.ec-lille.fr/~u3p/index.html

http://www.kp.dir.de/solarsail/

It is quite possible that the dawn of the new millenium portends a bright future for solar sails. Johnson and Schmidt discuss NASA plans for solar-sail technology-demonstration programs for the first decade of the 21st century. The first Near-Term Sail Demo mission, the 67-meter diameter Geostorm, has slipped from its planned 2001-2002 launch. Later in the decade, NASA hopes to launch a 100-meter diameter Mid-Term Sail Demo. Before 2010, NASA planned to launch a 150-300 meter diameter Advanced Sail Demo, which would reach the heliopause (at about 200 AU) after a 10-20 year flight.

Technology development efforts have taken longer and the budget emphasis has changed since these NASA plans were published. The efforts by NASA's Gossamer Space Structures and New Millenium Programs, L'Garde'sTeam Encounter, German company DLR's solar sail effort and others have led to slightly improved technology readiness of materials and structures for rectangular architectures. The Planetary Society's Cosmos 1 effort to unfurl a test sail in low-Earth orbit has also enabled improved technology for its multiple-vane sail architecture.

Taylor and Landrum (2000) have shown that the overall mass of a solar-sail spacecraft depends upon the architecture of the boom structure. According to their results, a hoop-supported sail structure is less massive than the square or rectangular boom-supported sail's cross members. This conclusion was independently verified by a participant at a Solar Sail Technology Interchange Meeting at the NASA Goddard Space Flight Center in spring 2001. Another topic discussed at that meeting was the importance of developing different architectures for different mission applications.

A more recent solar-sail technology assessment was held at the National Space Science and Technology Center (NSSTC) in Huntsville, AL in January 2002. The consensus was that the technology readiness of the square sail concept was high due to the historical emphasis on that design. It was also noted that there had been a historical lack of emphasis on multiple spacecraft architectures and their specific technologies. Many participants agreed that flight validation of solar-sail technology would be of great benefit.

As stated so eloquently in 1999 by McInnes, "*Since Garwin's paper initiated modern developments in solar sailing some forty years ago, the concept has inspired many individuals to devote their time and energy to advance the field. Countless technical papers have been written which demonstrate the potential advantages of solar sailing, many by graduate students who then move on to the more immediate problems of industry. Studies have been conducted which demonstrate the technical feasibility of solar sailing. However, for all these sometimes heroic efforts an operational solar sail has yet to fly.*"

A.2 History of Interstellar Solar-Sailing Concepts

Although the solar photon sail is a leading contender for humanity's next forays into the galaxy, the first rigorous considerations of the solar sail's applicability to extrasolar or interstellar space travel did not occur until the 1970's and 1980's. Although much of the research supported a British Interplanetary Society (BIS) study of the feasibility of interstellar travel, most of the researchers who participated in this phase of solar-sail research were Americans [see Mallove and Matloff (1989) and Mauldin (1992)].

Starting in 1974 and ending in about 1990, the BIS conducted work related to Project Daedalus, a study of a thermonuclear-pulse powered probe that could be accelerated to velocities of 0.15c and reach Alpha Centauri (at 4.3 light years from the Sun) or Barnard's Star (at about 6 light years from the Sun) in one-way, non-decelerated travel times of less than a human lifetime. This research has been summarized by Bond et al.

One of the major issues of the Daedalus study was fusion- fuel availability. To reduce irradiation by thermal neutrons, a mixture of helium-3 and deuterium was required. Because terrestrial helium-3 is very rare, Daedalus could be fueled (at great expense) by helium-3 mined from the atmospheres of the giant planets.

Editors of *JBIS (The Journal of the British Interplanetary Society)* acknowledged both the feasibility and difficulty of interstellar travel. They scheduled up to four annual issues of *JBIS* to concentrate on "Interstellar Studies." Because of helium-3's rarity and the socio-political issues relating to the acceptability of huge nuclear-pulse-propelled spacecraft, many *JBIS* authors considered alternatives to the interstellar thermonuclear-pulse rocket.

During the late 1970's, two American teams independently considered non-nuclear interstellar missions. In California, members of the NASA Jet Propulsion Laboratiry (JPL) team directed by Louis Friedman had published in 1978 their consideration of the feasibility of exploring Halley's comet in 1986 with a solar photon sail. Chaucey Uphoff, a member of this team, contributed to the JPL TAU study (Jaffe et al, 1980). This was a study of a probe to be launched in the early 21st century that could reach 1,000 AU from the Sun in a human lifetime, which requires a solar-system exit-velocity of about 100 km/sec.

TAU analysts concluded that only two propulsion systems are currently capable of performing the mission. The favored approach was the nuclear-electric or ion drive. Uphoff proposed as a back-up a hyperthin (less than 1 micron) solar photon sail unfurled within the orbit of Venus. Although Uphoff was merely credited with "unpublished calculations" in the final TAU report, his predictions compare well with those of the second group, whose results are in the literature.

Concurrently with the TAU study, Gregory Matloff collaborated with Michael Meotner in New York on the conceptual development of methods propelling directed-panspermia payloads on interstellar voyages of about 10,000- year duration. The preferred propulsion approach was to utilize a sailcraft with a lightness number (ratio of solar-radiation-pressure force to solar-gravitational force) of 1. If the sail of such a craft is directed normal to the Sun, it exits the solar system (according to Newton's 1st Law) along a straight-line trajectory at its solar orbital velocity prior to sail unfurlment. Mercury's orbital velocity is about 48 km/sec. Sail unfurlment near Mercury would result in a travetime to Alpha Centauri of about 27,000 years.

Meot-Ner and Matloff realized that lightness numbers in excess of 1 and sail-unfurlment distances within the orbit of Mercury would greatly reduce interstellar transit times. Analysis of these (and other) aspects of interstellar solar-photon sailing were published in the early 1980's by a team consisting of Matloff and Eugene Mallove.

Principal features of an interstellar solar-sail mission include an initial parabolic (or hyperbolic) solar orbit with a perihelion of a few million kilometers (the so-called "sundiver trajectory). At perihelion, the partially-unfurled sail is exposed to sunlight. If the sail is highly reflective, heat tolerant, and very thin, and the structure connecting sail and payload is sufficiently strong, solar-system exit velocities in excess of 1,000 km/sec are possible, even for large payloads.

This approach renders both robotic and peopled millenium-duration missions possible to the Alpha Centauri system. In a landmark 1984 paper, two Daedalus team members, Alan Bond and Anthony Martin, concluded that only one method of transferring human civilization to the stars--the thousand-year ark or worldship--would be feasible. And only thermonuclear-pulse or the solar photon sail would be up to the task.

Many subsequent papers have examined methods of reducing interstellar-solar-sail voyage duration. These include hyperbolic pre-perihelion velocities, application of hyperthin or perforated sails, and cables so thin that they are affected by radiation pressure [see Matloff (1983, 1984, 1996, 1997, and 2003). Computer simulations by Cassenti et al (1996) have revealed that various sail architectures are dynamically stable during the multi-g, hours-long near-Sun acceleration runs of solar-photon-sail starships.

McInes and Brown have pointed out that for perihelions within a few solar radii, the inverse-square law of solar irradiation needs correcting. Vulpetti (1986) and Cassenti (1997) have independently determined that their is some advantage in solar-system escape velocity if the solar-sail aspect angle relative to the Sun is optimized during pre- and post-perihelion trajectories. But all this work has not decreased interstellar-transfer times much below a millenium.

Recent Research : FOCAL, Aurora, and the NASA ISP

Starting in about 1990, international research began to focus upon near-term interstellar solar-sail missions. Rather than being directed towards nearby stars on millenial trajectories, these craft are conceived to examine the near-Sun interstellar environment out to a few thousand AU.

FOCAL (also called ASTROsail or SETIsail) originated through the efforts of the French astronomer Jean Heidmann and the Italian physicist Claudio Maccone. This is a proposed sail mission towards the Sun's gravitational focus at 550 AU. According to general relativity, electromagnetic radiation emitted by objects occulted by the Sun is focussed by the Sun's gravitational field into a narrow, highly-amplified beam, at and beyond the Sun's gravitational focus. Consider, for example, a sailcraft with a lightness number of 1 that first makes a close flyby of Jupiter to direct it into a parabolic solar orbit with a perihelion at the orbit of Mercury. Since the solar escape velocity at Mercury's orbit is 67 km/sec, the sailcraft will depart the solar system at this velocity. It will reach 550 AU about 40 years after launch. A long-lived spacecraft with a modest suite of astronomical instruments could use the Sun's gravitational focus to make observations of interest to astrophysicists and the SETI (Search for Extraterrestrial Intelligence) community.

Several FOCAL participants wondered whether a sailcraft could perform a scientifically useful function if directed towards targets closer than 550 AU. Further investigation led to Vulpetti's (1996) Aurora, a sailcraft carrying instruments to explore the near-interstellar environment out to about 200 AU. AS well as trajectory analysis, Aurora team members Genta and Brusca considered the design and stability of parachute-type sails with inflatable beam members. One Aurora innovation was the suggestion by Scaglione and Vulpetti that the mass of a tri-layer Earth-launched sail (aluminum reflective layer, chromium emissive layer, and plastic substrate) could be reduced by utilizing UV-sensitive plastic that would evaporate in space.

Beginning in 1998, NASA began to investigate a near-term (2010-2020) solar-sail launched heliopause probe. Perhaps inspired by Aurora, the Interstellar Probe (ISP) would carry particle- and field-measuring instruments to the boundary of the solar and interstellar space (which is about 200-AU from the Sun).

ISP propulsion options have been considered by Johnson and Leifer. To reach the heliopause in 20 years, the ISP must depart the solar system at about 50 km/sec, roughly 3X the speed of the Pioneer 10/11 and Voyager 1/2 probes. The total mission mass (excluding the sail) is about 150 kg, of which 30 kg are devoted to science instruments. According to Liewer et al, the sail's areal mass density is about 1 gm/m^2 and the sail mass is about 100 kg. In order to achieve its high solar-system exit velocity, the sailcraft must withstand a 0.25-AU perihelion pass.

As discussed by Garner et al, much progress on sail films and structures has occurred; much still remains to be accomplished. Recent work at NASA MSFC by Haggerty and Stanaland and Hollerman et al has included tests of candidate sail materials in the simulated and real space envioronment.

As reviewed by Matloff et al (2002), Vulpetti has applied Aurora-derived trajectory software to ISP. Application of direct or retrograde pre-perihelion trajectories allows two launch windows per year to reach any point in the near heliopause. Significant sail-size reductions or areal mass density are possible if the sailcraft departs Earth with a small hyperbolic excess velocity.

NASA has given some consideration to an "Oort Cloud Trailblazer" to be launched later in the 21st century. With a 0.1 gm/m^2 sail areal mass thickness, this craft could depart the solar system at 300 km/sec (0.001c) and travel more than 1,000 AU during its design lifetime.

A.3 Laser/Maser Photon Sailing History

Solar photon sailing is capable of propelling interstellar precursor probes and thousand-year arks to the nearest extrasolar star system. The beamed-energy photon sail, on the otherhand, is the only physically feasible mode of interstellar transport that is conceptually capable of two-way interstellar travel, with transit times approximating a human lifetime. Althogh many researchers (notably Marx, Moeckel, and Norem) contributed to the early theoretical development of this concept, most of the concepts were more fully explored by Robert Forward.

As discussed in literature reviews by Mauldin (1992), Mallove and Matloff (1989) and Matloff (2000), Forward began his examination of this concept in the early 1960's. The basic challenges for both early and recent researchers in this field were :

(1) How do we project a human-carrying spacecraft to a nearby star within a human lifetime?

(2) How do we accomplish this task with known physics?

(3) Can we constrain mission energy requirements and projected costs to acceptable levels?

(4) Finally, can we return the crew (or their children) to Earth at the conclusion of their interstellar exploration?

Attempts to address these challenges have certaibly been creative. But not all of these attempts will prove to be feasible.

One limitation to laser / maser applicability to interstellar propulsion was realized almost immediately. This is the requirement of maintaining beam collimation and aim to an accuracy defined by a 100-1,000 km sail over a trillion-kilometer acceleration "runway."

Assume that the disc-sail diameter normal to the energy beam is D_{sail} and the separation between the aperture of the energy beam and the light sail is $DIS_{tran\text{-}sail}$. At a selected transmitter-sail separation, the angle (θ) subtended by sail is D_{sail} / $DIS_{tran\text{-}sail}$. If we wish, for example, to project a collimated electromagnetic-energy beam against a 1000-km diameter at a distance of 10^{12} km, we must point the beam to an accuracy of 10^{-9} radians. Beam drift nust be eliminated or compensated for and the transmitter must maintain its alignment in spite of gravitational perturbations by solar-system objects. Such perfection must also be maintained for decades over distances so large that the speed-of-light limitation renders feedback between power station and starship impossible.

Mission designers can improve things a bit by selecting a short beam wavelength (λ_{laser}) and a large beam-transmitter aperture diameter $D_{laser\text{-}tran}$. Applying Rayleigh's criterion (see Chap. 1),

$$\theta = \frac{D_{sail}}{DIS_{tran-sail}} = 2.44\frac{\lambda_{laser}}{D_{laser-tran}} . \tag{A.1}$$

One way to reduce the requirement for a long beam-collimation length is to utilize a spacecraft that can make several passes through the energy beam. A suggested approach is thrustless Lorentz-force turning. If the sailcraft is charged to a significantly high electrical potential after leaving the power beam, the influence of the local galactic magnetic field will alter its trajectory [see Norem (1969) and Forward (1964). Conceptually, the sailcraft could circle back and reenter the beam. Magnetic alternatives to charged surfaces have also been suggested. But as discussed in Matloff (2000), Geof Landis has informed author Matloff that they are probably infeasible.

Although thrustless turning may be feasible, it may not be practical. We do not know for what duration of time a sufficiently large electrical charge can be maintained on a spacecraft moving at high speed through the interstellar plasma. We also have no idea regarding the constancy of the interstellar magnetic field over the light-year radius of a thrustless turn.

As discussed in Chap. 7, Forward (1985) suggested perforated sails as a means of reducing spacecraft mass. Unfortunately, the semi-empirical theory utilized by Forward to estimate performance of a perforated light sail only applies for the case of a superconducting sail. Could even a very-high temperature superconductor remain superconducting when pelted by gigawatts of electromagnetic radiation?

Matloff (2003) has applied the theoretical approach discussed by Driscoll and Vaughan to estimate spectral reflectivity, transmissivity, absorptivity and emissivity of a non-superconducting, metallic, perforated light sail (see Chap. 7). Although an improvement, this theory applies only for very restrictive mesh-design parameters. Much theoretical and experimental work must still be done before the advantages of perforated light sails are demonstrated. However, as pointed out by Landis (2000), our current theoretical understanding may be sufficient for us to conclude that, in the absence of very high-temperature superconductors, metallic meshes may have less of an advantage over metallic thin-film sheet sails than initially assumed. Landis (1989, 1999) has suggested that dielectric thin-sheet sails may be superior to both metallic mesh and sheet sails for interstellar light-sailing application.

In 1984, Forward suggested that beam collimation could be maintained over interstellar distances by locating a thin-film Fresnel lens in the energy beam between the transmitter and sail. The potential and problems of applying Fresnel lenses in space has been reviewed in 2003 by James Early. Although such lenses are physically feasible, maintaining an optical link over trillions of kilometers for three elements (transmitter, lens, and sail) is a significant engineering challenge.

If the engineering challenges are solved, two-way interstellar travel might be possible using laser-pushed lightsails. In 1984, Forward proposed an interstellar mission utilizing sails and Fresnel lenses in the 1,000-km range and laser powers of about 4×10^{16} watts (about 1,000X current terrestrial-civilization's power consumption). In this analysis, a spacecraft massing 8 X 10^7 kg is accelerated by the beam towards the star Epsilon Eridani, which is 10.8 light years from the Sun.

A multi-stage laser sail would be used to enable two-way interstellar travel in the following manner. After acceleration, one sail segment would be detached and maneuvered into the power beam. Light relected from this sail would be projected against the starship sail to decelerate it at Epsilon Eridani and later accelerate the starship back towards Earth. Approaching the solar system once again, the starship would again enter the power beam for deceleration. Total round-trip travel time could be less than a human lifetime.

Many less-ambitious alternative missions have been suggested. As suggested by Kare, we might accelerate micro-sails (less than 1 meter in diameter) in the energy beam. After acceleration, these would be steered to impact a much larger starship,which would be accelerated by momentum transfer. According to Nordley, such an approach might require intelligent micro-sails capable of homing in on the larger spacecraft.

Leik Myrabo et al (2000,2003) has reported experiments with model spacecraft in power beams, both in vacuum and the atmosphere. Other recent experimental and analytical work by Benford et al (2002,2003) has concentrated upon the stability of beam-riding spacecraft. It seems (as Matloff confirmed in 2001) that certain sail shapes may be able to automatically correct for a small amount of beam drift.

Most considerations of laser / maser sailing assume a beam-transmitting power station in a constant inner solar-system position between the Sun and starship. Because this may be difficult to achieve, Matloff and Potter (1996) have analyzed the case of a non-fixed power station, in which the power station follows the starship on a trajectory that is slightly hyperbolic relative to the Sun.

It is usually assumed that Rayleigh's criterion implies that short-wavelength laser power beams will always be superior to microwave maser beams. But this may not always be true.

Discussions with a number of microwave researchers (including G. and J. Benford and S. Potter) reveal that although operational microwave technology is currently applied to 1-cm microwaves, this technology could be modified for application to millimeter-wavelength microwaves. The economies of microwave technology (as compared with high-energy laser technology) could therefore be realized with shorter-wavelength microwaves.

But of potentially greater significance (if the idea proves to be feasible) is an application from general relativity. Claudio Maccone (2001) has investigated propulsive application of the Sun's gravitational focus. Electromagnetic radiation emitted by an object occulted by the Sun will be focussed by solar gravity into a highly amplified and very narrow beam at a minimum distance of 550 AU from the Sun. The Sun-occulted object must itself be at least 550 AU from the Sun.

Matloff (2003b) reasons that it may be possible to tailor the wavefront of emissions from a solar-powered maser much closer to the Sun than 550 AU to have the same curvature at the solar limb as emissions from a source at 550 AU. If this can work, the maser radiation from the power station will be concentrated in a narrow beam beginning at 550 AU on the far side of the Sun and beam collimation will be maintained for a very large distance.

Further discussions with Maccone reveal that many factors, including variations in the coronal plasma, may render this idea unfeasible. But it is certainly worthy of further study.

Very-Large Space-Based Laser Concepts

As discussed in the web site http://www.optopower.com, current diode-laser-array technology can produce output irradiances of about 10 MW/m^2. The beam diameter is small; diode arrays are not complicated and require only collimating optics, a power supply and a radiator to remove heat from the diode material. The diode lasers are less efficient than, for example, solar-pumped gas lasers, but their simplicity in design makes them a good candidate for laser sailing.

Assume an interstellar laser-sailing mission in which a 1,000-kg spacecraft is to be accelerated to 0.15c during ten years and the sail diameter is 1 km. If laser irradiance on the sail is constant, the sail acceleration is about 0.14 m/sec^2, or about 0.015g. Assuming a 0.9 sail reflectivity and applying Eq. (7.2), the required laser power impinging against the sail is about 2 X 10^{10} watts. The laser-beam irradiance on the sail is about 2.5 X 10^4 watts/m^2, about equivalent to the irradiance of a solar sail 0.25 AU from the Sun.

If each laser diode array can generate 20 W, about 1 billion diode arrays are required. Assuming that each diode array has dimensions of 1 mm by 0.5 mm by 3 mm (including the heat sink), the surface area of the emitting plane of the diode array is 5 X 10^{-7} m^2. The total dimension of required diode arrays will be about 30 m.

According to DeYoung et al, diode lasers operate at about 30% efficiency. THe solar-cell collector array must therefore generate about 67 GW of power. At 1 AU from the Sun, solar-cell array will have a radius of about 8 km, assuming a solar-cell efficiency of 0.25. . Placing the collector closer to the Sun will reduce its size.

Large Optical Components

Most papers on interstellar laser sailing acknowledge the fact that large optics are required to direct the laser / maser emissions from the solar-system based power station against the distant starship sail. The type of optic usually assumed, the O'Meara para-lens, was introduced by Robert Forward in 1984. Shown schematically in Fig. A.2, this device is essentially a large Fresnel lens made of concentric rings of low-mass, transparent material. The para-lens is constructed in such a way that there are concentric voids between the rings; support spars are used to give the structure structural integrity.

Although many authors have mentioned the para-lens, few have attempted a detailed diffraction analysis. In a preliminary 1989 analysis, Mallove and Matloff sugested that a reflective optic would function better. Taylor et al (2003) have published a diffraction analysis of a sample 500-m diameter O'Meara para-lens designed to focus 500 nm laser light against a 500-m diameter sail at a distance of 2 light years. The results of this effort indicate that reflective optics are both more efficient and easier to engineer than the para-lens for this application.

Pointing and Tracking

Very precise control is required to keep the laser beam on the sail at interplanetary or interstellar distances. The beam-focussing optic could be adjusted using control vanes, in a manner analogous to control-vane application to solar sails. However, some method of making very precise pointing adjustments is essential. Coneptually, this could be affected at the laser aperture by adjustments to the diffractive optics. Even the best pointing and tracking systems have pointing errors due to system vibrations, optical imperfections, etc. This system "jitter" effectively tilts the beam at an angle to the optical path. Following Taylor and Landrum (2001), the center of the beam is then moved away from the center of the target by:

$$\Delta r_{jit} = D_{laser-tran} j_{po\,\mathrm{int}} , \qquad \text{(A-2)}$$

where j_{point} is the pointing jitter. For the beam's center to remain on the sail, the maximun allowable jitter is calculated by equating Δr_{jit} to the sail radius.

Figure A.3 presents pointing jitter vs. interplanetary distances for the 500-m radius sailcraft previously considered. As discussed by Possel, the state-of-the-art in tracking and pointing jitter is about 0.1 microradians. To maintain the beam on sail for 100 AU requires an improvement in pointing jitter of about 4 orders of magnitude. As demonstrated in Fig. A.4, current pointing-jitter technology must improve by 9 orders of magnitude to enable laser acceleration over interstellar distances.

Because the spatial distribution of the pointing error is a random Gaussian variable, the Central Limit theorem requires the irradiance distribution over a given time interval to fill in a radial Gaussian distribution. Using Arnon's formalism,

$$IRR(r.d.) = IRR(o)e^{\frac{r.d.^2}{2\sigma_{jit}^2}} \quad , \qquad \text{(A-3)}$$

where IRR(o) is beam central irradiance in watts/m^2, IRR(r.d.) is beam irradiance at radial dimension r.d. kilometers, and σ_{jit} is the standard deviation of beam jitter or jitter amplitude, in km. The jitter amplitude is calculated using :

$$\sigma_{jit} = \Delta r_{jit} = D_{laser-tran}\, j_{po\,\mathrm{int}} \quad . \qquad \text{(A-4)}$$

Since the distribution mapped out by the laser beam is radially symmetric, it may not be necessary to maintain the laser on the sail at all times. If the sail can maintain its location near the beam center, it will still be illuminated symmetrically and follow the Gaussian profile. The loss of incident beam energy due to jitter is determined using the above anaylsis as a function of distance from the main steering optic of the laser. The time-integrated laser-beam profile for a distance of 10 AU is presented as Fig. A.5.

If we assume that our sail remains near the center of the beam and that the sail radius is 500 km, Eq. (A-3) is integrated between 0 and 500 m at a distance of 10 AU to indicate that about 0.025% of the total beam is incident on the sail. Assuming a 67 GW laser array, at 10 AU there will still be about 20 W/m^2 incident on the sail, which is about 1.5% of the solar constant. Figure A.6 presents the percentage of incident power on the sail vs. distance. Improving the jitter will, of course, improve the incident laser beam power.

Large Controllable Space Mirrors and Antennas : Concepts and Experiments

Although it is often assumed in laser-sailing discussions that the laser beam is collimated by the optical system, Forward (1984) suggested that the para-lens should be utilized to focus the beam slightly beyond the lightsail, to insure that the entire beam is incident upon the lightsail.

To alter the focus of the para-lens would require changing spacing and width of the refractive rings--a difficult if not insurmountable task. But this task matches the capabilities of an inflatable or electrically-controlled membrane reflector. As the sail distance from the reflector increases, inflation pressure or electrical-field strength should be decreased--increasing the radius of the reflector's catenary curve and increasing the distance to the focus.

Therefore, the reflector is an active optical element. Teledyne Brown Engineering, Inc, in Huntsville, AL, has conducted research on the practicality of electrically-addressable membrane optics. The electrically optic developed in this project is described by Taylor et al (2002, 2003). It can be pixillated, which allows for beam steering and wavefront correction.

This experimental electrically addressed optic consists of two plates of conducting aluminum separated by a given distance. A high-voltage static field between the two plates is used to contour the surface optic. Electrostatic forces pull the plates together into a catenary (parabolic-like) shape. By varying the field strength across the pixellated control surface, the reflector's surface flatness is controlled adaptively. Experiments reveal that the refector can be maintained flat within optical wavelengths for reflector diameters greater than 5 meters. Contol at larger (infrared or microwave) wavelengths should prove easier due to the larger wavelengths.

The figure of the laser-reflector surface would be sensed in space using a variant of the common astronomical "Star Test" in which the Airy disc of visible or infrared starlight would be continously viewed. Corrections would automatically be made by applying perturbation voltages to tiles on the control membrane. A controller has been designed to correct for both static deformation of the reflector and dynamic effects such as thermal cycling or structural vibrations.

To demonstrate proof-of-concept, a small-scale prototype of the optic / antenna has been constructed. As shown in Fig. A-7, the circumference of a 1-meter diameter piece of 1 mil (0.0025 cm) thick aluminized Kapton polymide film was bonded to an elastic fabric. A circular hole was cut in a foam board frame; a flat reflective surface was created by securing the fabric to the frame. The fabric's elasticity tensioned the film and kept it flat in the de-energized state. At intervals around the film's perimeter, connections were made to the aluminum coating. These were attached to the positive terminal of a high-voltage power supply.

Another solid sheet of foam board with aluminum foil bonded to it was placed behind the reflective film. The negative terminal of the power supply was connected to this surface.

A satellite-television LNBF (low-noise block converter) with integrated feed horn was connected to a satellite receiver and mounted on an adjustable arm in front of the reflector. The assembly was placed in a location where it could view the Sun. High voltage was applied, which curved the reflector and focused the sunlight. Due to film-surface imperfections, the focused sunlight produced a 20-30 cm diameter spot size. The support arm was used to place the LNBF at this focus. The LNBF was connected to the satellite receiver and the antenna assembly was aimed at an orbiting satellite transmitting at 11.7-12.2 GHz. Tests revealed that to insure satellite-signal acquisition, the aperture of the conical feed horn must exceed 10 cm.

After acquiring the satellite's signal, high voltage was removed. This caused the film to relax and the signal was lost. Application and removal of high voltage resulted repeatedly in acquisition and loss of the satellite's signal. This experiment confirms that the electrostatically-produced reflector curvature constitutes a practical antenna.

The prototype was constructed using commercially available material with no controlled tolerances or precise mechanical adjustments. Optimized materials, controlled tolerances, and accurate component placement would greatly improve antenna efficiency.

It was also demonstrated than the film's curvature was proportional to the separation between film and ground plane and the voltage difference. This proportionality was evident from the movement of the focal point and diameter of the spot.

A.4 Architecture Analysis : Square Sails vs. Hoop Sails

As mentioned earlier in this Appendix, the most analyzed photon-sail architecture is the square or rectangular sail. Here, we attempt to rectify this imbalance by comparing a typical square-sail design with a hoop-supported sail. the analysis compares the mass and lightness factor of the two sails. Each sail has an identical area of 10^6 m^2; the square sail is 1,000 m on a side, the hoop-sail's diameter is 1,128.6 m.

We assume a square-sail supported by four booms, with an optimistic boom linear density (λ_{boom}) of 0.05 kg/m. We also assume an optimistic sail , σ_{sail}, of 0.001 kg/m^2. The mass of the hardware required to connect spacecraft components is M_{hw} and the payload mass is M_{pay}. The mass of the square sailcraft can now be expressed as :

$$M_{squaresail} = \sigma_{sail} L^2 + \frac{4\lambda_{boom} L}{\sqrt{2}} + M_{payload} + M_{hw} \,, \qquad \text{(A.5)}$$

Assuming a reflectivity coefficient of 0.85, the square-sailcraft lightness factor can be calculated by applying Eq. (4.19) :

$$\eta_{squaresail} = 0.00146\left(\frac{L^2}{M_{squaresail}}\right) . \qquad \text{(A-6)}$$

If we assume a payload mass of 150 kg and a hardware mass of 50 kg, the total mass of this square sailcraft is 1,343 kg. The square sailcraft's lightness factor is 1.09.

If this sailcraft is unfurled at perihelion of a 0.1 AU parabolic solar orbit, the solar-system escape velocity at perihelion is 133 km/sec. Applying Eq. (4.27), the sailcraft exits the solar system at 139 km/sec or about 20 AU/year.

Now consider the hoop-supported sail with the same area,with the spacecraft identical in design to the Oort Cloud Explorer described at the end of this Appendix but with a diameter of 1128.6 m rather than 850 m. The mass of the hoop sailcraft is 1,201 kg and the areal mass thickness is 0.0012 kg/m^2. Applying Eq. (4.19) once again for 0.85 reflectivity, the lightness factor of the hoop sail is 1.21. For the same sail-unfurlment strategy as the square sail, the hoop sail exits the solar system at 146 km/sec or about 21 AU/year.

Figures A.8 and A.9 respectively show the lightness factors of square and hoop sails vs. sail area. The hoop sail has a slightly higher lightness factor until sail areas exceed 3 X 10^7 m^2, due to less structural-support mass.

A.5 Energy/Momentum Conservation in a Perfect Solar Sail

Sometimes, it is productive for practioners in newly emerging fields to review the fundamentals. Such a situation occurred during the summer of 2003 when a critique of the basic physics assumptions of solar sailing was issued on the Web by Cornell University astrophysicist Thomas Gold (http ://aexiv.org/html/physics/0306050 and http://www.newscientist.com/news/news.jsp?id=ns99993895). Events leading up to these Web publications are described by Louis Friedman of The Planetary Society (http://www.planetary.org/solarsail/ss_and_physics.html).

Gold correctly pointed out that under somewhat reduced atmospheric pressure, the blades of Crooke's Radiometer (also called a Light Mill--a device with a vertical shaft equipped with horizontal blades coated white and black on alternate sides--see

http://math.ucr.edu/home/baez/physics/General/LightMill/light-mill.html) turn in the opposite direction from what would be expected from photon-pressure assumptions. In response, solar-sail researcher Bemjamin Diedrich
(http://www.ugcs.caltech.edu/~diedrich/solarsails/newscientistletter.html)
responded that the correct (thermal) explanation for the spin of Crooke's Radiometer was suggested by the Scottish physicist James Clerk Maxwell about 130 years ago. Under high vacuum conditions, in fact (as pointed out in
http://www.physics.brown.edu/Studies/Demo/thermo/demo/4d2010.htm)
the radiometer's spin direction reverses as predicted by radiation-pressure theory.

Diedrich also pointed out that Carnot's 19th century thermodynamics theory (Ohanian, 1989) cannot be correctly applied to an open system such as a solar sail. This conclusion was independently reached by Travis Taylor and communicated to NASA MSFC solar-sail manager Edward Montgomery on June 25, 2003.

Other researchers responded to Gold's challenge by investigating various aspects of basic photon-sail physics. Matloff developed a simple demonstration that both energy and linear momentum are conserved in the operation of a photon sail.

Energy/Momentum Conservation in a Perfect Solar-Photon Sail

It is possible to demonstrate that a perfectly-reflecting photon sail obeys both conservation laws. Consider the situation presented in Fig. A.10. The reference frame is positioned on a perfectly reflecting solar sail with mass M_{sail} at time t=0. A photon of wavelength λ approaches the sail with a momentum of $P_{phot,o}$, before it interacts with the sail. At time $t=\Delta t$, the photon rebounds with momentum $P_{phot,1}$. Now the sail moves with velocity ΔV_{sail} relative to the reference frame.

From elementary quantum theory (Sears, et al 1980), the linear-momentum change of the photon during perfect reflection from the sail is :

$$\Delta P_{phot} = P_{phot,1} - P_{phot,o} = -\frac{2h}{\lambda}, \qquad \text{(A-7)}$$

where h=Planck's Constant. In this momentum equation, the wavelength change of the reflected photon is considered to be inconsequential.

The linear-momentum change of the sail during photon reflection is $M_{sail} \Delta V_{sail}$. Assuming that linear-momentum is conserved during the interaction of the photon and the sail :

$$\Delta V_{sail} = \frac{2h}{\lambda M_{sail}}. \qquad \text{(A-8)}$$

During its interaction with the photon, the sail's kinetic energy (ΔKE_{sail}) increases by :

$$\Delta KE_{sail} = \frac{1}{2} M_{sail} \Delta V_{sail}^2 = \frac{2h^2}{\lambda^2 M_{sail}}. \qquad \text{(A-9)}$$

The wavelength of the reflected photon will be very slightly different from the wavelength of the incident photon according to the electromagnetic (EM) Doppler Effect, or "Red Shift" (Stodolkiewisz, 1976). The reflected photon will have a different kinetic energy from the incident photon, as expressed by :

$$\Delta KE_{phot} = \frac{hc}{\lambda} - \frac{hc}{\lambda + \Delta\lambda} = \frac{hc\Delta\lambda}{\lambda^2}, \qquad \text{(A-10)}$$

since the incremental velocity change is very much smaller than the velocity of light.

According to the EM Doppler Effect, $\Delta\lambda / \lambda = \Delta V_{sail}/c$. Therefore, we can express the decrease in photon kinetic energy as :

$$\Delta KE_{phot} = \frac{h \Delta V_{sail}}{\lambda} .$$

(A.11)

We next substitute our expression for ΔV_{sail}, Eq. (A.8), into Eq. (A.11) to obtain the following expression for photon kinetic energy decrease :

$$\Delta KE_{phot} = \frac{2h^2}{\lambda^2 M_{sail}} , \qquad \text{(A.12)}$$

which is identical to Eq. (A-9) for the increase in sail kinetic energy. Thus, both conservation laws apply to the perfectly-reflecting photon sail.

Experimental / Operational Tests of Photon Sailing

As Diedrich points out, we have now obtained excellent experimental and operational evidence confirming the principle of photon sailing. As well as being measured in laboratory experiments since about 1900, solar-radiation pressure was observed during the 1960's to alter the orbits of the Echo balloon satellites, according to theoretical predictions. Solar-radiation pressure was also applied to steer the Mariner 10 fly-by mission to Mercury and has been used in orbital adjustments and attitude control of communication satellites.

The in-space propulsion community owes a significant debt to Prof. Gold. As the solar photon sail begins to emerge from the theoretician's blackboard as an operational space-propulsion system, a review of basic physical principles is a very good thing.

A.6 Mission Concept 1 : A Lunar Microsail

Early photon-sail demonstration missions could be conducted in cis-lunar space. These could be unfurled from the space shuttle or an expendable booster, with a small upper stage used to project the sail and payload to orbital heights of about 1,000 km, where atmospheric drag becomes inconsequential.

Figure A.11 shows a possible architecture for such a micro-spacecraft. Based upon the hoop-sail concept, this craft could deliver a 2.5-kg payload to lunar orbit or impact within 2 years. The probe consists of five 3.41-m diameter hoop-supported sails connected to each other as shown in the figure. The central sail disc supports the outer four, which can be rotated for guidance and control. Payload is suspended in the center of the main central hoop. This can be moved on guidewires to alter the spacecraft center of mass for steering purposes.

The simplicity and low mass of this spacecraft renders it inexpensive to launch (perhaps as a secondary payload) and easy to deploy. The outer hoops can fold inward on top of the central hoop, for easy storage within the launch vehicle. The payload is about the size of a shoebox and the total spacecraft mass is less than 5 kg. One small launch vehicle could hypothetically deploy a "swarm" of these lunar hoop sails.

As discussed in Taylor et al (2003), a 3.6-m diameter hoop-supported sail has been demonstrated in the laboratory. Finite element analysis reveals that a hoop 2-cm in diameter and 50-microns thick has sufficient strength to support the sail membrane under solar illumination and deployment. Analysis of launch-stress capabilities has not yet been conducted.

A.7 Mission Concept 2 : Geostorm / Solar-Sentinel

One early photon-sail application of high interest is to locate a photon sail or flotilla of sails at the L1 Lagrange Point in the Earth-Sun system. A spacecraft at L1 is 1.49×10^6

km closer to the Sun than the Earth and are located where gravitational influences of Sun and Earth balance, so that, with minimal orbital adjustment, the spacecraft can maintain its position for a long period of time.

Solar space observatories at L1, such as the Advanced Composition Explorer (ACE) launched in 1998, provide early warning of solar flares and Coronal Mass Ejections, since the particles emitted during these events reach the observatories about one hour before they reach the Earth. Not stationary at L1, they are in "halo" orbits perpendicular to the Earth-Sun line, centered on L1.

NASA is considering a solar-photon sail L1 solar observatory. This observatory, dubbed Geostorm, would have a long lifetime. Sail adjustments would be used to maintain the spacecraft's halo orbit, rather than on-board thrusters. The main limitation on useful lifetime would be sail survivability in the 1-AU solar environment.

Taylor (2003) describes a detailed analysis of Geostorm-sail dynamics. Aspects considered include the calculation of equilibrium points for a solar photon sail in the Sun-Earth system, the stability of the sail at these equilibrium points, control of solar photon sails near the Sun-Earth line, and calculations of minimum-time heliocentric solar photon sail trajectories.

A.8 Mission Concept 3 : Comet Rendezvous and Comet-Nucleus Sample Return

As shown in Table A.1, many comets have perihelions within 1 AU. A solar-photon sail comet probe should be capable of matching orbits with a selected inner-solar-system comet, flying in formation with that comet, gathering a sample of comet material and returning to Earth.

Such a mission would have great public and scientific interest. Comets often dominate the sky during their close solar approaches, or "apparitions." Human reaction to these celestial visitors has occasionally altered the course of history (Sagan and Druyan, 1985). In 1986, space probes from Europe, Japan, Russia, and the US conducted fly-by or fly-through encounters with Halley's Comet.

Comets sometimes strike the Earth, altering the ecology and biosphere. As well as causing mass extinctions, such impacts have brought volatile substances (including water) to the Earth's surface. A comet sample-return mission would address scientific questions about these sky objects. What is the tensile strength of comet nuclei--very significant if we wish to alter a comet's course and protect the Earth? What complex organic compounds--the progenitors of life--are present in the layers surrounding the nucleus?

Comets represent the primeval solar system and may be similiar in properties to the galactic nebula from which the solar system evolved. A comet sample-return mission could even check the very controversial hypothesis that life evolved in this nebular preceeding the evolution of the planets (Wickramsinghe et al, 1997).

A comet-rendezvous mission will have several phases. These include:
(1) Launch from Earth, (2) Comet Orbit Matching and Rendezvous, (3) Formation Flying and (4) Sample Return. Before considering these phases, we turn attention to selection of a comet for our proposed sample-return mission and the mathematics of proposed mission.

Candidate Comet Selection

A listing of short-period comets that have made repeated visits to the inner solar system is included in Binzer et al (2000). At least 18 comets regularly visit the inner solar system. Nine of these have aphelia between 4.09 and 6.19 AU (these may have been influenced by Jupiter). Eight have inclinations between 0 and 20 degrees; four have inclinations between 21 and 61 degrees; three have inclinations between 61 and 100 degrees; and three have inclinations 101-180 degrees. The average inclination of the orbit of one of these comets to the ecliptic is 47.3 degrees. The average comet in this class has a perihelion of 0.74 AU and the average comet's eccentricity is 0.844.

As further justified in Taylor et al (2003b), the comet chosen for the proposed sample-return mission is 107P Wilson-Harrington, also called Minor Planet 4015. This object has a perihelion of 1 AU, which reduces the requirement for spacecraft solar-orbit adjustment; it orbits the Sun every 4.29 years, which allows ample mission opportunities; and its inclination is only 2.8 degrees, which reduces the requirement for inclination "cranking." The eccentricity (e_{com}) for Comet 107P is 0.623 and its aphelion is 4.29 AU.

Sailcraft Design Parameters

Both disc and square sails have been considered for this mission. Both craft carry a payload of 50 kg and use a sail areal mass thickness of 0.006 kg/m^2. This is not an unreachable sail-film areal mass thickness in 2003. The sail reflectivity is assumed to be 0.9

The disc sail has a radius of 50 m. It is assumed that structure increases sail mass by a factor of 1.3. The spacecraft areal mass thickness is 0.012 kg/m^2. From Eq. (4.19), the lightness factor is 0.12. The total spacecraft mass is about 115 kg. Applying Eq. (4.17) and assuming that the sail is oriented normal to the Sun, its acceleration at 1 AU from the Sun is 7.3 X 10^{-4} m/sec^2.

The square sail is 100 m on a side and the structural booms have a linear density of 0.05 kg/m. The spacecraft areal mass thickness, lightness factor, and characteristic acceleration are essentially identical to that of the disc sail.

The Mathematics of Comet and Sailcraft Orbits

The comet's velocity at perihelion can be determined using an equation from Eq. (6.49) of Fowles (1962):

$$V_{peri} = V_{circ}(e_{com} + 1)^{1/2} , \tag{A.13}$$

where V_{circ} is the circular velocity at the comet's perihelion distance from the Sun. If we modify Fowles' Eq. (6.51), we can relate perihelion velocity to circular velocity, perihelion Sun-comet separation (R_{peri}) and aphelion Sun-comet separation (R_{aph}):

$$V_{peri} = V_{circ} \left[\frac{2R_{aph} / R_{peri}}{1 + \left(\frac{R_{aph}}{R_{peri}} \right)} \right]^{1/2} . \qquad \text{(A.14)}$$

Since we know the spacecraft velocity at perihelion (relative to the Sun) and the perihelion distance, we can orbital energy at perihelion to orbital energy at any other solar distance (R_{so}), assuming no orbital energy change. Orbital velocity at position R_{so} is calculated :

$$V_{so} = [V_{circ}^2 - 2.65X10^{20} \frac{(R_{so} - R_{peri})}{1 + R_{aph} / R_{peri}}]^{1/2} . \qquad \text{(A.15)}$$

It is assumed that the first maneuver after Earth escape is an inclination change at a constant distance from the Sun. We have performed a curve-fit to McInnes (1999) Eq. (4.23) to obtain :

$$\frac{\Delta I}{\Delta t} = \frac{\eta_{s/c}}{0.05} \exp[-1.323 \ln(R_{co}) - 2.3] ,$$

(A.16)

where $\Delta I/\Delta t$ is the inclination change in degrees per week, $\eta_{s/c}$ is the spacecraft lightness factor, and R_{co} is constant inclination "cranking-orbit" distance from the Sun, in AU.

As the sail's orbit is adjusted, its angle is not always normal to the Sun. We can relate the acceleration of a back-reflective photon sail tangential to its solar orbit (ACC_t) to its acceleration when oriented normal to the Sun (ACC_{norm}) and the angle,θ, (between the normal to the sail and the line between the sail and the Sun using Eq. (50) of Forward (1990) :

$$ACC_t = ACC_{norm} \sin\theta \cos\theta \quad \text{(A.17)}$$

Mission Phase 1 : Earth Departure

Because of the low spacecraft mass, Delta / Atlas-class rockets are more than capable of launching the sailcraft. We suggest a high-energy upper stage so that the Earth-escape (or hyperbolic excess) velocity of the sailcraft is about 3 km/sec. This is the same Earth-escape velocity required to insert an Eath-launched spacecraft into a Mars-bound Hohmann-transfer ellipse, as discussed by Bate et al.

The sail should be unfurled after Earth escape, used first for inclination cranking, then to rendezvous with the comet and finally to return to Earth. One option is to use an upper stage capable of supplying an 8 km/sec hyperbolic excess velocity (equal to that required for a Jupiter-bound Hohmann transfer. Then, the sail need be used only for inclination cranking and Earth return.

Mission Phase 2 : Inclination Cranking

If we apply Eq. (A.16) for this spacecraft and the selected comet, we find that at 1 AU, the 2.8-degree inclination change takes 12.7 weeks or about 90 days. Of course, since the spacecraft will not always be at 1 AU and will not always be normal to the Sun, perhaps 100 days should be allocated for this maneuver. Within 2 years, an inclination change of 22 degrees is possible, bringing 8 comets in Binzer et al's list within reach.

Mission Phase 3 : Comet-Orbit Matching

Asuming that angle $\theta = 45$ degrees, we can apply Eq. (A-17) to the spacecraft designs selected. A tangential acceleration of 3.25×10^{-4} m/sec^2 is quite possible. This is equivalent to a tangential velocity change of about 10 km/year, which is more than sufficient for comet rendezvous, station-keeping, and return to Earth.

Applying Eq. (A-13) to Comet 107P, we find that the comet is about 8 km/sec faster than the Earth at perihelion. Less than a year of orbit-matching maneuvers is required, for a 3-km/sec Earth-escape velocity.

For comparison, McInnes has considered a comet-rendezvous mission for a sail with a lightness factor of 0.05. Even for such a massive spacecraft, comet rendezvous requires no more than 5 years.

Mission Phase 4 : Station-Keeping and Sample Collection

We propose a novel approach to sample collection. While the sail is used to maintain the position of the spacecraft perhaps a few hundred kilometers from the comet nucleus, a sample can of perhaps 0.0004 m^3 volume is lowered to the comet's nucleus, attached to the sailcraft by a tether. The sample container's launch mechanism could be a spring.

Station keeping with an active comet near perihelion engenders some risk of damage to a gossamer sailcraft. As discussed by D. R. Williams in the 2003 website http://nssdc.gsfc.nasa.gov/planetary/giotto.html, the 1986 European Space Agency probe to Halley's Comet was impacted by a dust particle energetic enough to shift the spacecraft's trajectory by 0.9 degrees. But as discussed by B. G. Marsden in another 2003 website (http://cometography.com/pcomets/107p.html), Comet 107P is a relatively inactive object that undergoes infrequent outbursts, even during apparition. Furthermore, Giotto flew through the coma of Halley's Comet in March 1986 with a velocity relative to the comet of about 60 km/sec. This comet-sample return sailcraft has a velocity relative to the comet close to 0 km/sec during sample collection.

During descent and ascent of the sample container, the sailcraft could maneuver to avoid particles emitted from the nucleus of Comet 107P. The sample container would be equipped with a descent and ascent stage. The landing pads would be coated with an substance such as synthetic Gecko skin. As described by Autumn et al, Geckos are small reptiles with feet equipped to adhere to almost any surface, even in vacuum, by van der Waals forces. A counter-rotating drill system is proposed in Taylor et al (2003b) to collect the samples. After sample collection, the ascent stage of the lander would simply detach from the ascent stage and be wheeled slowly up to the sailcraft. The stage separation could be spring loaded.

Mission Phase 5 : Earth-Return

With its comet-nucleus samples, the sailcraft would return to the vicinity of Earth by reversing the maneuvers described above. Since the sail is still functional, no additional thrusting is required for capture by the Earth. The sample container can be retrieved from the sailcraft after Earth-capture for examination in space, or returned to Earth in a reentry capsule.

One option for Earth-return is discussed in greater detail in the following section and in Matloff and Taylor (2003). It is possible to utilize the sail parachute-fashion in the upper fringes of a planet's atmosphere so that the sailcraft is captured by that planet.

A.9 Mission Concept 4 : Neptune Rendezvous Using Sail Aerocapture

We propose a mission to Neptune that is launched to Earth-escape. The photon sail is then unfurled and oriented normal to the Sun. The sail is sufficiently thin that the spacecraft can achieve solar-system escape velocity; it is retained (and possibly oriented parallel to the Sun-spacecraft line) during the post-acceleration cruise to Neptune.

Approaching Neptune at the solar excape velocity at Neptune's orbit, the sail is oriented normal to the direction of travel. The sail is used parachute fashion to decelerate by atmospheric drag in Neptune's upper atmosphere. After deceleration, the spacecraft has been captured as an eccentric-orbit satellite of Neptune. If the sail survives its pass through the giant planet's atmosphere, it can be used for orbital adjustment.

Sailcraft Design Parameters

The design is based upon "Persephone"--a Neptune / Kuiper-Belt probe considered by Matloff (2001c). The sail areal mass thickness is a challenging (but probably achieveable by 2010) 0.001 kg/m^2. The total spacecraft mass is 300 kg, half of which is sail. About 30 kg is alloted to the science payload. Like the proposed NASA Interstellar Probe, the sail radius is 219 m (Johnson and Liewer, 2000 and Matloff et al, 2002). Assuming a 90% sail reflectivity, Eq. (4.17) can be used to demonstrate that the acceleration of the sailcraft at 1 AU is about 0.0043 m/sec^2, if it is oriented normal to the Sun.

The original Persephone proposal assumed sail unfurlment after Earth escape and acceleration to solar parabolic or escape velocity. The spacecraft then makes a close approach to Neptune, firing its (chemical) rockets in reverse deep within Neptune's gravity well (see Chap. 4 for a discussion of powered gravity-assist maneuvers. The craft then cruises at reduced velocity to a Kuiper belt object near Neptune, depositing a landing probe on the surface of that object using chemical rockets. Here, deceleration into Neptune orbit uses the sail alone and requires no thrust.

The Pre-Neptune-Encounter Mission Phases

As before, we assume a Delta / Atlas-class launcher and sail unfurlment after Earth-escape. The sailcraft initially travels at a velocity of 30 km/sec relative to the Sun. To achieve solar-escape velocity, this velocity must be increased to 42 km/sec. At the acceleration described above, solar-escape is reached at 1 AU after one month.

The sailcraft then cruises to Neptune, which is located about 30 AU from the Sun. Applying Eq. (1.3), we find that the spacecraft reaches Neptune about 12.7 years after launch.

From Tholen et al, Neptune orbits the Sun at 5.48 km/sec. The solar-system escape velocity at Neptune's orbit is therefore 7.75 km/sec. Also from Tholen et al, Neptune's equatorial escape velocity is 23.71 km/sec. Applying Eq. (4.12), the velocity of the spacecraft relative to Neptune at the start of aerobraking is $[(7.75)^2 + (23.71)^2]^{1/2}$ or about 24.94 km/sec. To be captured as a satellite of Neptune, the spacecraft must reduce its velocity relative to the planet by 24.94-23.71=1.23 km/sec.

The Physics of Sail Aerobraking

As a spacecraft passes through a planet's atmosphere, it encounters atmospheric molecules. This interaction decelerates the spacecraft by atmospheric drag, according to the equation (Harris and Spencer, 1965):

$$ACC_{drag} = -0.5 C_d \rho_{atm} A_{sail} \frac{V_{s/c}^2}{M_{s/c}} \approx -\frac{\rho_{atm} V_{s/c}^2}{\sigma_{s/c}}, \qquad \text{(A.18)}$$

where the minus sign denotes deceleration, C_d is the drag coefficient (usually equal to 2--

2.3), ρ_{atm} is the planet's atmospheric density, A_{sail} is the sail area normal to the line of flight, $V_{s/c}$ is spacecraft velocity relative to the planet's atmosphere, $M_{s/c}$ is the spacecraft mass, and $\sigma_{s/c}$ is the spacecraft areal mass thickness during aerobraking.

Perhaps the first question to address is how much acceleration typical sail designs can withstand. This was addressed in a finite-element analysis of the structural stability of three types of solar-photon sails, that was published by Brice Cassenti et al in 1996. Three types of solar-photon sails (parachute, inflatable, and parabolic) were examined during hypothetical high-acceleration, close-perihelion maneuvers required for interstellar solar sailing. (The parabolic sail configuration examined is Robert Forward's two-sail Solar Photon Thruster concept published in 1990). All three sail configurations can withstand 2.5 g, or about 25 m/sec^2, using feasible structural arrangements and materials.

Next we consider what happens physically during the high-speed run through a planet's atmosphere. The choices for an atmospheric atom encountering the sail are:

(a) the atmospheric atom penetrates the sail;

(b) the atmospheric atom causes sail atom-plane dislocations;

(c) the atmospheric atom ionizes a sail atom;

(d) the atmospheric atom excites a sail atom, which later emits a photon and returns to the ground state.

Option (a) is very unlikely. This is because the atomic spacing in a solid lattice is of the same order as the atomic size (Kittel, 1962). Impacting atmospheric atoms will probably not result in sail atom-plane dislocation. Also from Kittel (1962), 5-10 electron volts of energy are required to dislocate a lattice-atom plane. Sail-atom ionization is also unlikely because (as demonstrated by Matloff and Taylor, 2003), impacts by many atmospheric atoms are required to ionize a ground-state aluminum atom and the lifetime of a typical excited state is less than a microsecond. So option (d), which results in sail heating by impacting atmosphere atoms, is the most likely.

As discussed by Matloff and Taylor (2003), this conclusion should be tested by experiments. Interaction with chemically active upper-atmosphere species may certainly degrade a photon sail. But similiar devices--large balloon satellites--have survived for years in the rareified upper reaches of Earth's atmosphere.

An Isodensity Planetary Atmosphere Model and Its Application to Screening Calculations

Exact calculation of an aerocapture pass requires calculation of sailcraft deceleration in atmospheric layers of varying density--a laborous process not easily amenable to analytical solution. Instead of examining aerocapture using numerical-integration techniques, we present here an approximation based upon constant atmospheric density. Comparison with numerical integration indicates that this approach is accurate to a few percent.

Figure A.12 presents the simplified geometry of an aerocapture pass. The sailcraft is within the planet's atmosphere when the height above the surface is less than $h_{s/c,o}$. At the center of the aerocapture pass of length D_{ac}, the height of the sailcraft above the planet's visible surface is $h_{s/c,m}$. The radius of the planet (in this case Neptune), is R_{nep}.

If we apply the Pythagorean relationship to the situation in Fig. (A.13), we can relate $h_{s/c,o}$ to $h_{s/c,m}$:

$$h_{s/c,o} = \left[(D_{ac}/2)^2 + (h_{s/c,m} + R_{nep})^2 \right]^{1/2} - R_{nep} \quad .$$

(A.19)

This can, of course, be applied to any celestial body with an atmosphere, if the appropriate radius is used.

The next step was the derivation of an approximate density profile for Neptune's exosphere. This was derived using the Voyager data of Broadfoot et al ;

$$\rho_{atm,nep} \approx \left(4X10^{-11}\right)\exp\left(\frac{1000 - h_{s/c}}{300}\right) \text{ kg/m}^3, \qquad \text{(A.20)}$$

which is fairly accurate in the spacecraft height range ($h_{S/C}$) 1,000-4,000 km. In this equation, spacecraft height is in kilometers.

In Eq. (A.20), the denominator of the exponential term, 300 km, is equal to the density scale height. To insure a near-isodensity atmosphere, the aerocapture profile selected must be such that the numerator of the exponential term is much smaller than the denominator.

A Neptune-Aerocapture Profile

We consider the following scenario. The sailcraft approaches Neptune in a solar parabolic orbit, as discussed above. It must reduce its velocity relative to the planet from 24.94 to 23.71 km/sec, or by 1.23 km/sec, to be captured as a satellite of Neptune.

Conservatively, we limit average deceleration to 1 g, or about 10 m/sec^2. Aerocapture duration is therefore about 123 seconds. Since the sailcraft's average velocity relative to Neptune during aerocapture is about 24 km/sec, the distance traversed during aerocapture (D_{ac}) is about 3,000 km.

We next apply Eq. (A.18) for our sailcraft areal mass rhickness of 0.002 kg/m^2. The atmospheric density at the center of the Neptune aerocapture pass is about 3.47 X 10^{-11} kg/m^2 . From Eq. (A.20), the sailcraft height above the planet's visible surface (or cloud tops) at the center of the aerocapture pass ($h_{S/C,m}$) is about 1,000 km.

According to Lodders and Fegley (1998), the equatorial radius of Neptune at the 1-bar atmospheric pressure level (R_{nep}) is 24,764 km. We next apply Eq. (A.19) to estimate the height above the Neptune cloud tops at the start and conclusion of the aerocapture pass ($h_{S/C,O}$) as 1,044 km. Since the difference between central and edge aerocapture heights is very much less than the density scale height, the isodensity approximation works very well for this profile.

Thermal Effects During Aerocapture

It is assumed from previous discussion that all sailcraft kinetic energy shed during the aerobraking pass must be radiated by the sail. For this aerocapture profile and spacecraft design, the sailcraft kinetic energy relative to Neptune decreases by 9 X 10^9 Joules during aerobraking.

We next divide this decrease in sailcraft kinetic energy by the duration of the aerocapture pass (123 seconds), to find the average sail radiated power during aerocapture, about 7.3 X 10^7 watts.

This spacecraft has a sail area of about 1.5 X 10^5 m^2, so the approximate average electromagnetic flux radiated by the sail during aerobraking is about 480 watt/m^2. Recalling that both sail faces can radiate, we apply the Stefan-Boltzmann law (see Chap. 4) for a sail emissivity of 0.6 to obtain the average sail radiation temperature during aerocapture, 290 Kelvin. Thermal constrants do not unduly stretch current sail technology, in this instance.

Modified Mission Profiles

It seems likely that further analysis will result in many alternative mission profiles. We could elect for a faster Neptune-transfer, perhaps by unfurling the sail closer to the Sun than 1 AU. This would reduce the trans-Neptune transfer time.

Alternatively, rigorous aerocapture calculation may demonstrate the existence of decreased g-loading. This would reduce thermal and structural constraints during aerocapture.

A.10 Mission Concept 5 : An Oort Cloud Explorer

Here, we consider what might be the ultimate Earth-launched solar-photon sail. It is a hoop sail, which has perhaps 50% the performance of the space-manufactured solar-photon sails considered in Chap. 4.

Consider the spacecraft configuration presented in Fig. (A.13). This design was originally published by Taylor et al (2003a). The sail film has a diameter of 681 m and an areal mass thickness of 10^{-4} kg/m^2.

As shown in the figure, the sail is supported by an inflated torus or hoop. Steering and attitude control is provided by four smaller 5-m diameter hoops. Total structural mass is calculated at 50 kg using state-of-the-art materials and the payload mass is 150 kg.

The total mass of the sailcraft is the sum of sail-film mass, payload mass, structural mass, main-hoop mass, steering-hoop masses, and inflation-gas mass. Making reasonable assumptions about achieveable masses, the sailcraft areal mass thickness is approximately 6.5 X 10^{-4} kg/m^2. The total spacecraft mass is therefore about 240 kg.

If a 0.85 sail reflectivity is assumed, Eq. (4.19) can be used to calculate the spacecraft lightness factor, $\eta_{s/c}$. For the configuration examined, this parameter is approximately 2.3.

To reach the Oort comet cloud in a flight time approximating a human lifetime, it is necessary to unfurl the sail as close to the Sun as possible. Solar-system escape velocities for such "sundiver" trajectories can be approximated in two ways. We can assume an elliptical pre-perihelion trajectory and utilize Eq. (6.15) of McInnes or assume a parabolic pre-perihelion trajectory and apply Eq. (4.27) of this book. Both approximations yield similiar results for close perihelion passes and both assume that the sail is normal to the Sun (not always optimal, as shown by Vulpetti, 1996a).

At 0.01 AU from the Sun's center, the solar-escape velocity is about 420 km/sec. Substituting in Eq. (4.27), we find that the sailcraft exits the solar system at about 635 km/sec or about 130 AU/year. Thus, the Oort Cloud explorer could reach the inner fringe of the solar-system's Oort comet cloud, a few thousand astronomical units from the Sun, after a flight of a few decades. It is interesting to note that this spacecraft could cross the 260,000 AU gulf between the Sun and Proxima/Alpha Centauri in approximately 2,000 years, roughly twice the travel time of the best physically possible space-manufactured solar-photon sails.

The 550-AU gravitational-focus of the Sun is reached in the fifth year of flight. So one scientific goal of the craft could be to check the predictions of relativity and rival theories about the gravity focus, and to possibly exploit a location beyond the Sun's inner gravity focus to perform astrophysical observations, as reviewed by Heidmann and Maccone (1994).

Science in the Oort cloud will be challenging. The spacecraft will be light days or light weeks from Earth and will therefore require a great deal of on-board intelligence and autonomy. Cameras and other instruments used to gather data on comets along the spacecraft track must be both very sensitive because of the low solar illumination levels and very fast because of the high sailcraft velocity.

Mechanical design of this sailcraft will be challenging as well, since the solar-radiation-pressure acceleration at perihelion will be about 12 g. Sail perihelion temperature can be estimated from Eq. (4.21). Assuming a 0.6 sail emissivity and full sail unfurlment at perihelion, the sail perihelion temperature will be about 2,300 Kelvin--which also presents major challenges to sailcraft designers.

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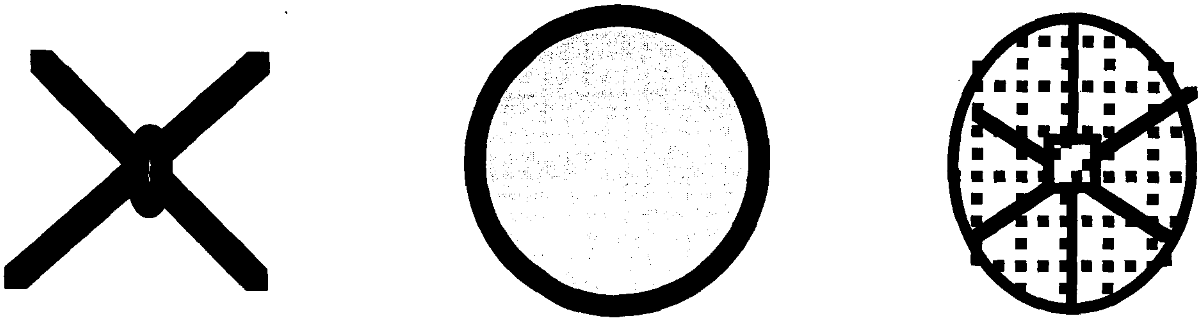
Fig. A.1 Various Solar-Photon Sail Architectures

Square sail with diagonal booms. Payload in center.

Parachute sail. Payload supported by cables.



Heligyro with payload at center.

Hoop-supported saill. Distributed payload could hang from hoop.

Spinning-Disc Sail Payload in center.

Fig. A.2. The O'Meara Para-Lens

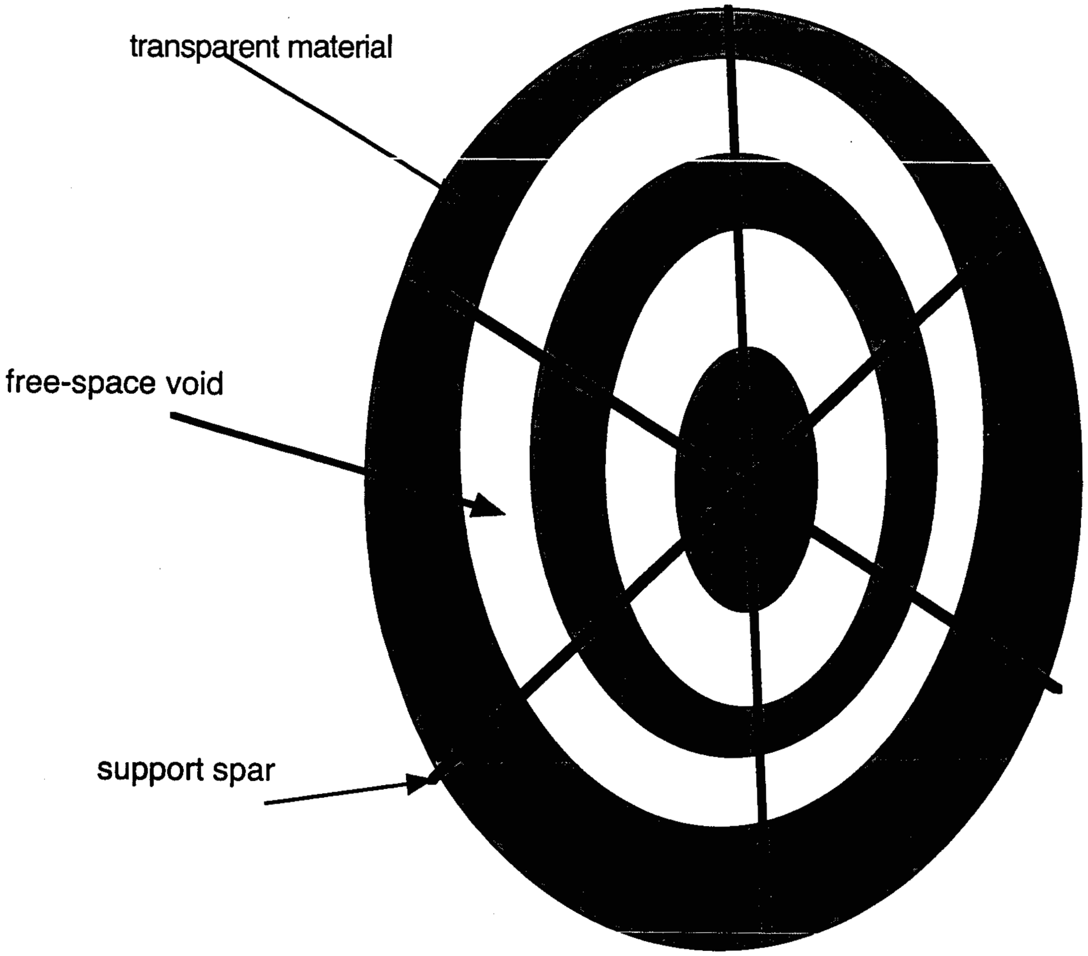


Fig. A.3. Pointing Jitter vs. Distance (AU)

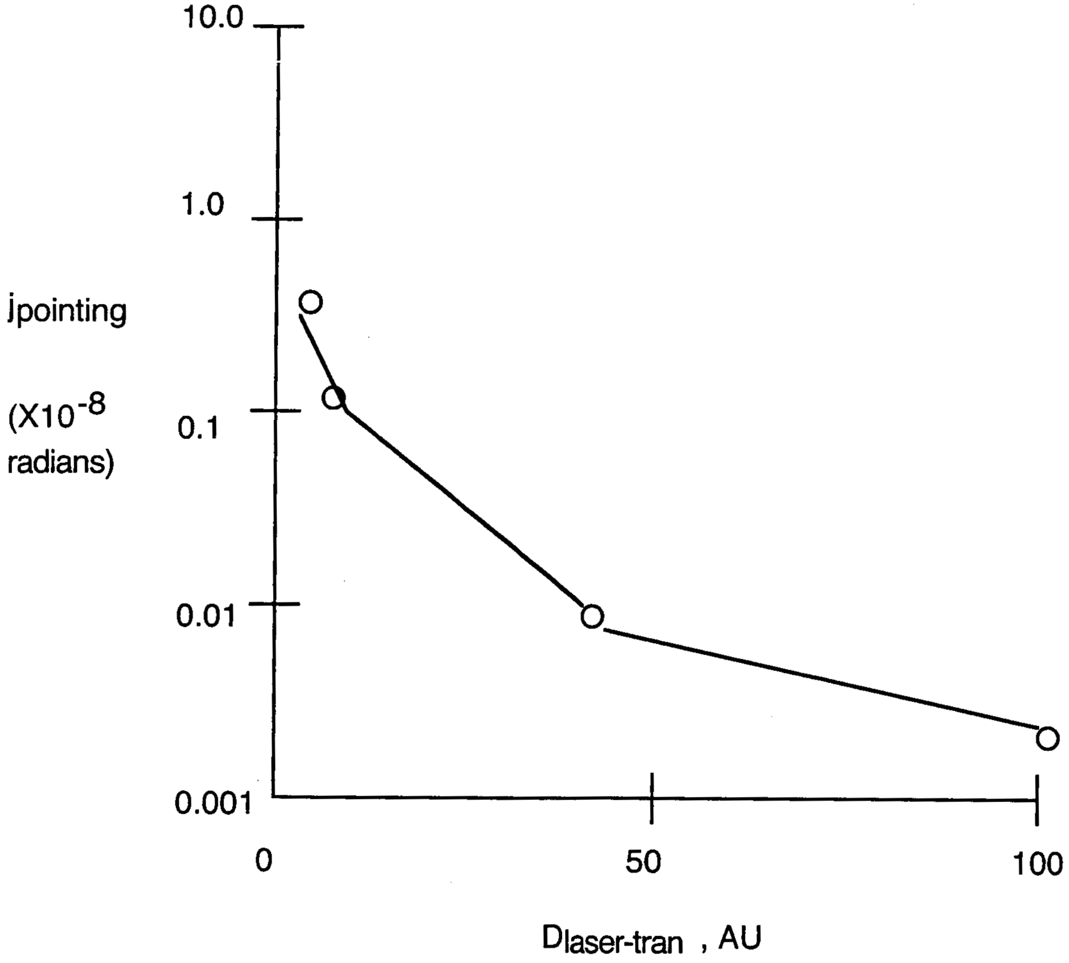


Fig. A.4. Pointing Jitter vs. Distance (light years)

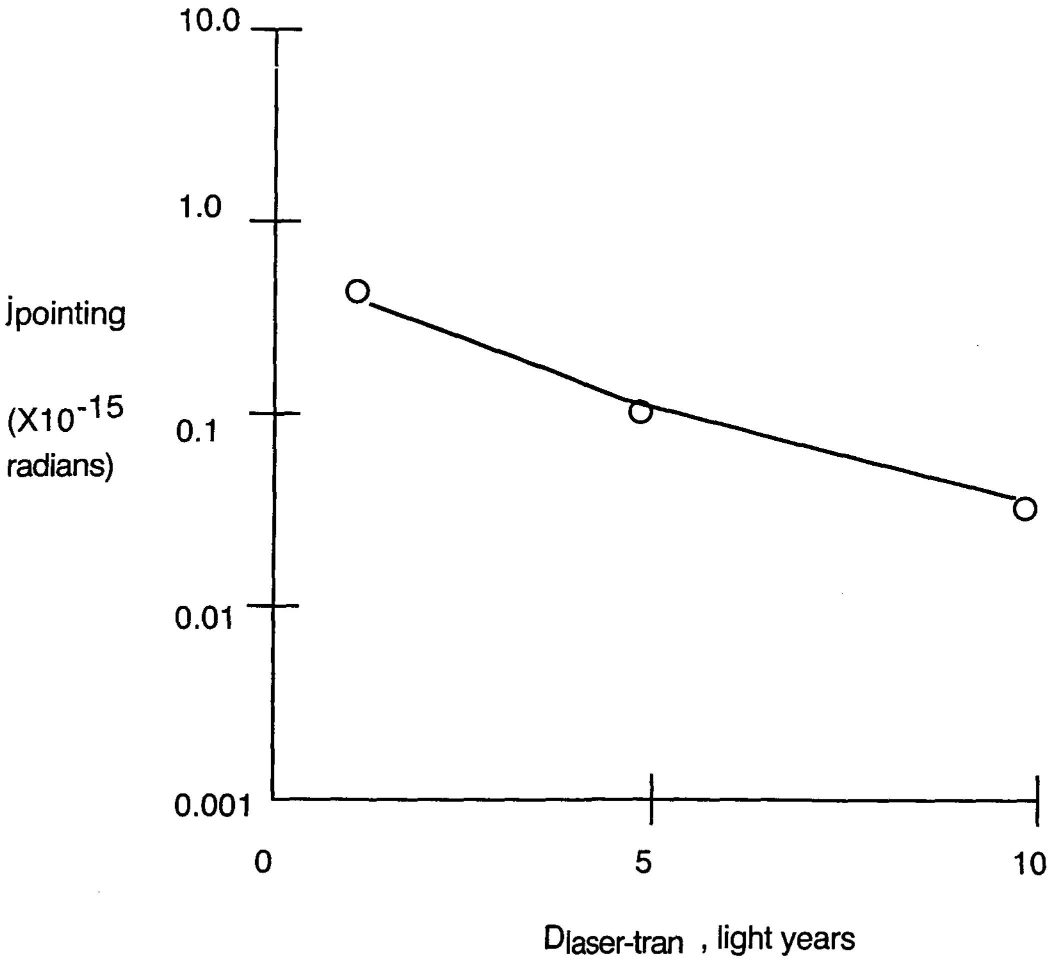


Fig. A.5. Time integrated laser beam profile at 10 AU

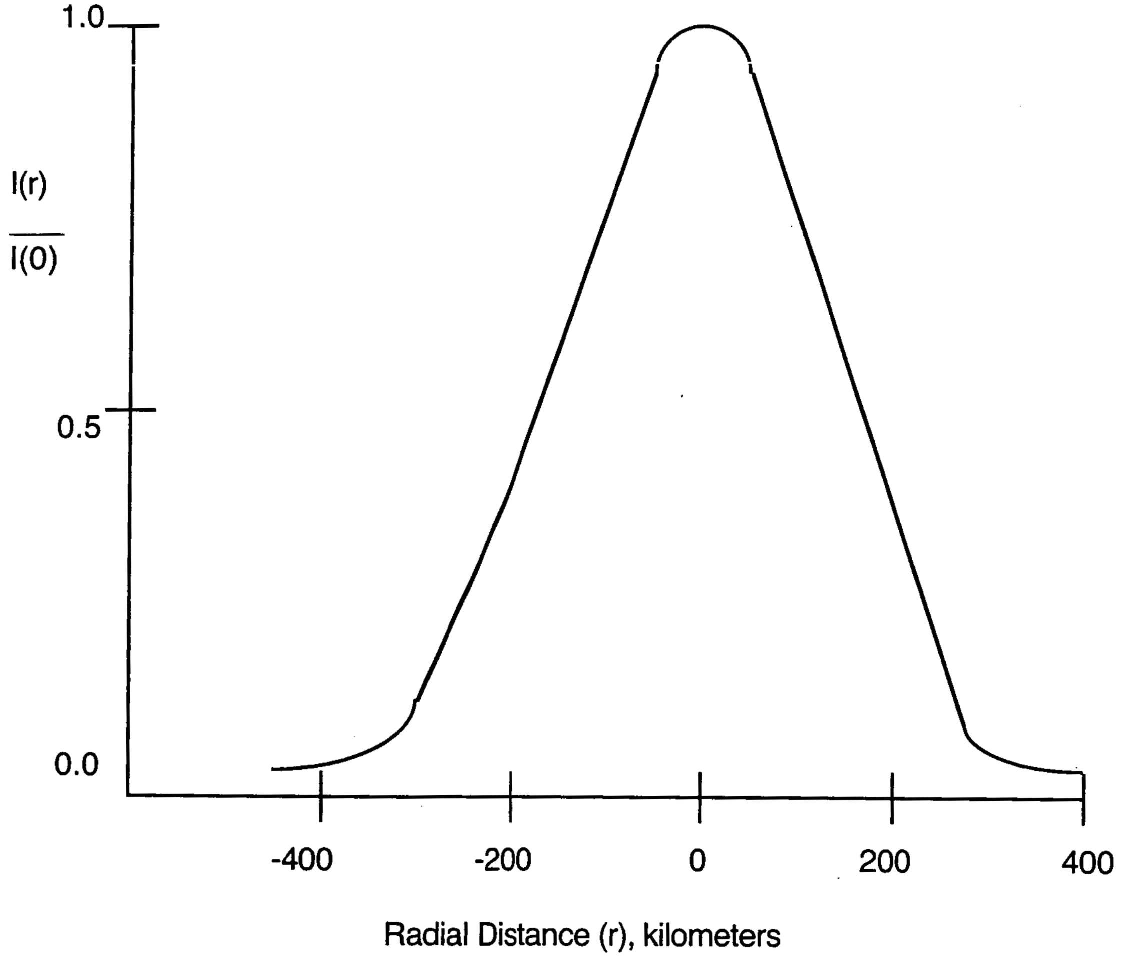


Fig. A.6. Percent of laser power incident on sail vs. distance

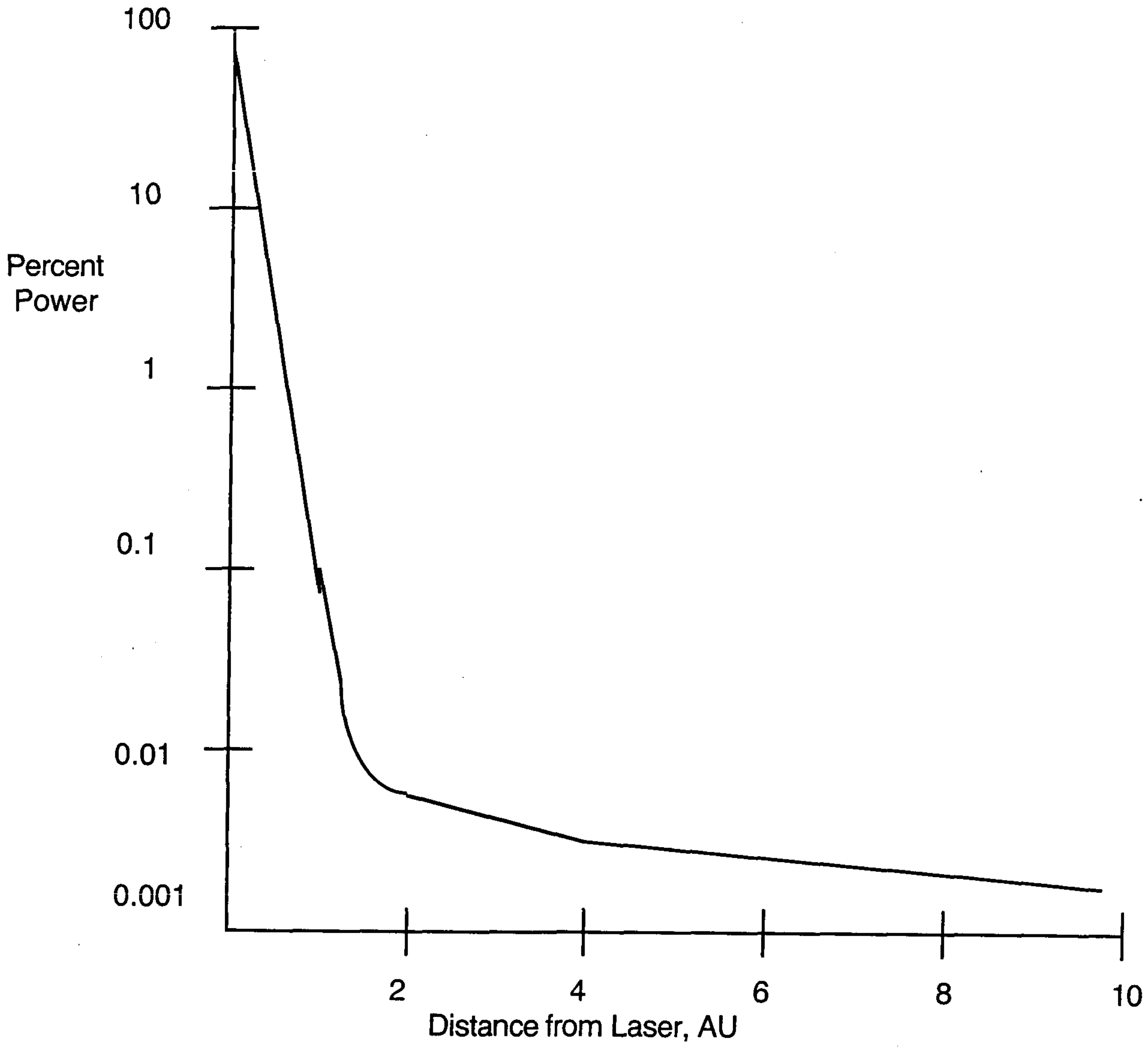


Fig. A.7. Schematic of Membrane Antenna Experiment

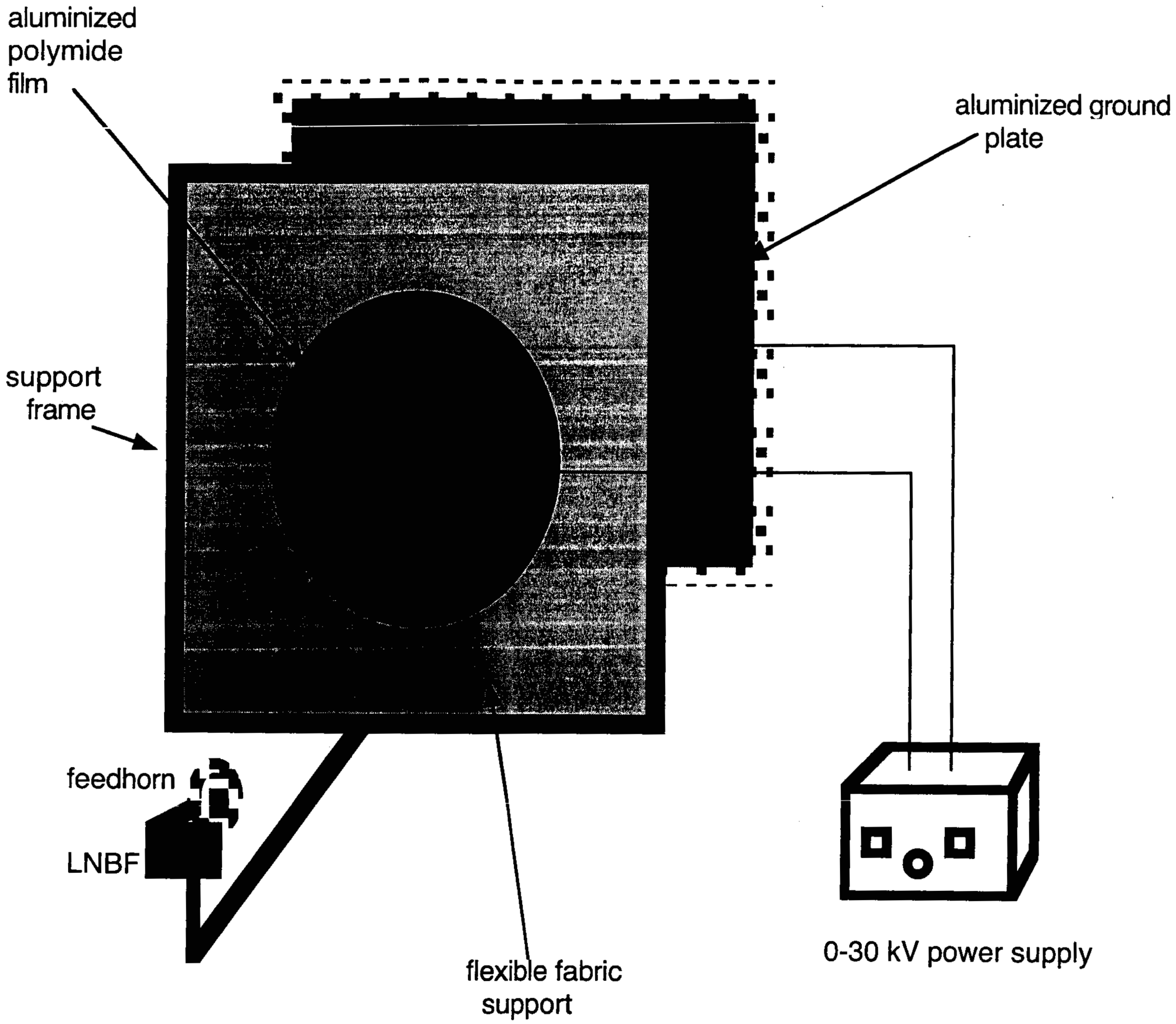


Fig. A.8. Lightness Factor of Square Sail vs. sail Area

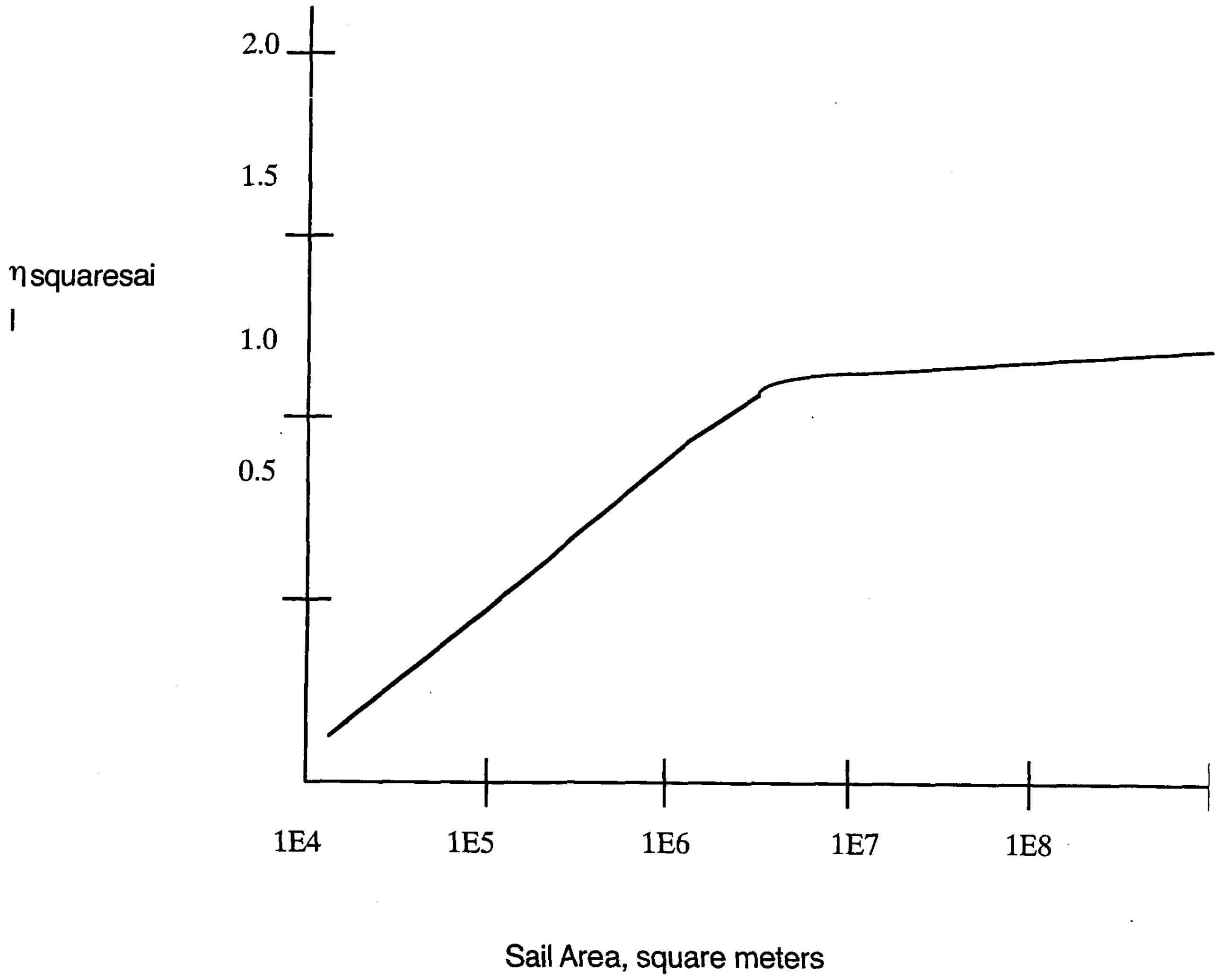


Fig. A.9. Lightness Factor of Hoop Sail vs. sail Area

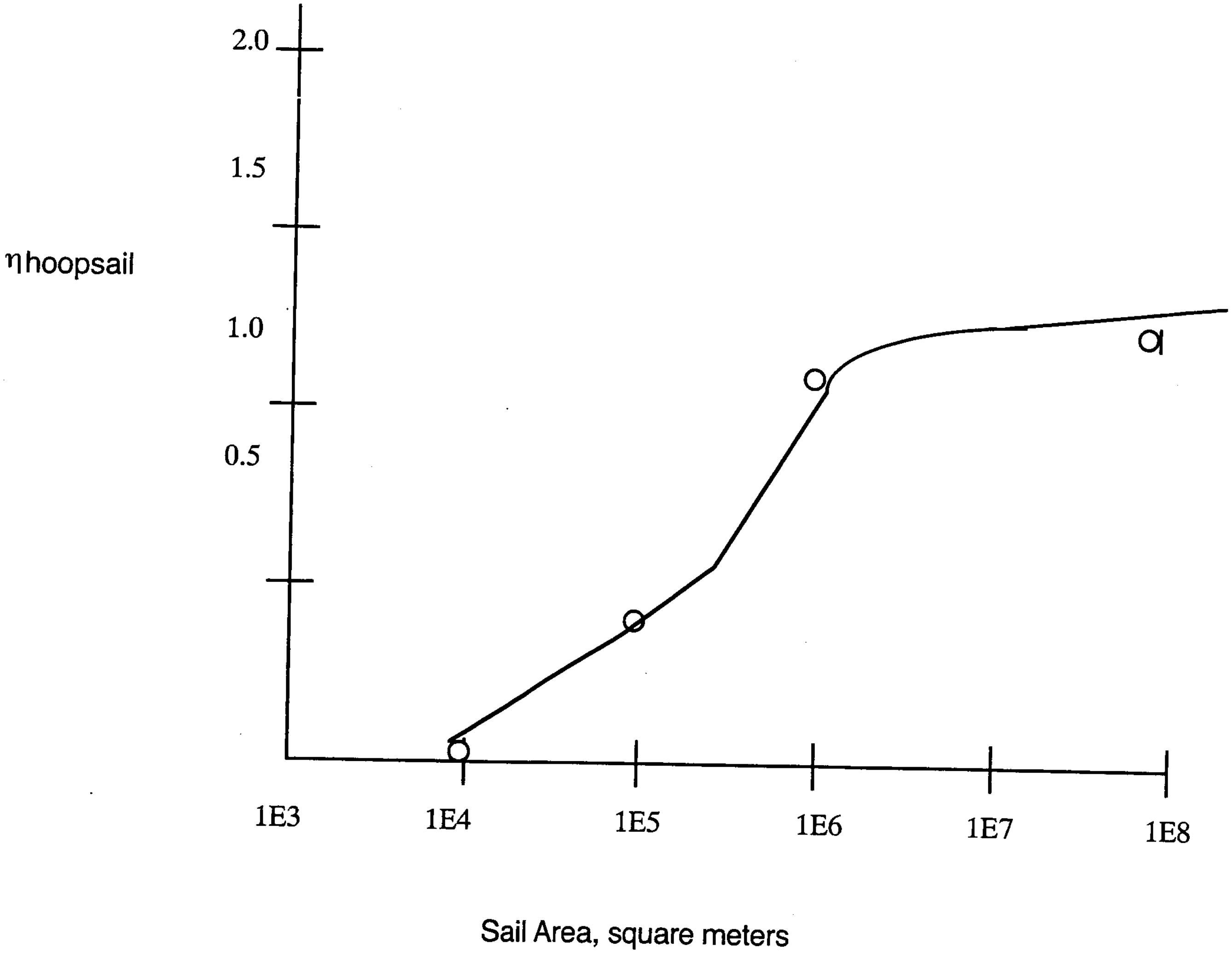
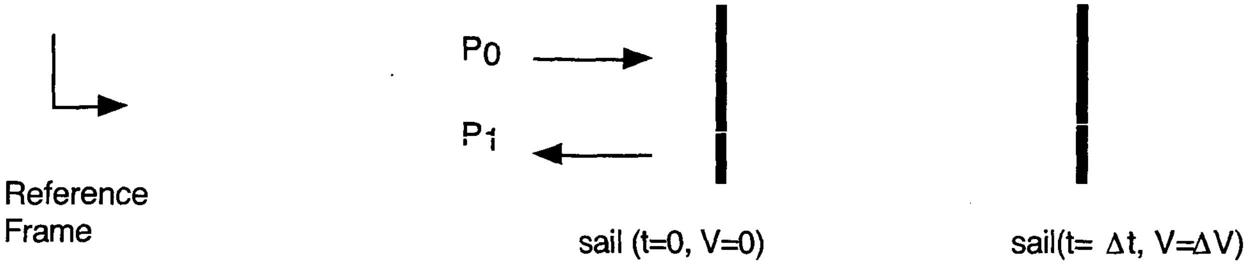


Fig. A.10. Solar-Sailing Energy and Momentum Conservation



<u>KEY</u>

t=time , V=velocity, P = momentum

P_0 = photon momentum berfore reflection

P_1 = photon momentum after reflection

Fig. A.11. Configuration of a Lunar Microsail

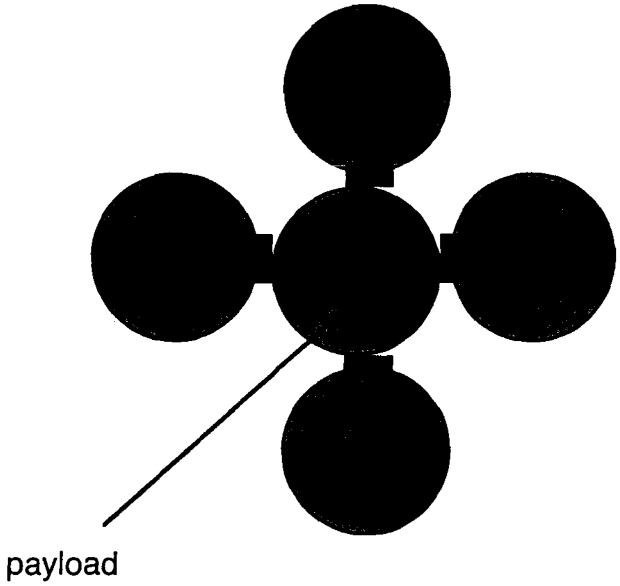


Fig. A.12. Neptune Aerocapture-Pass Geometry

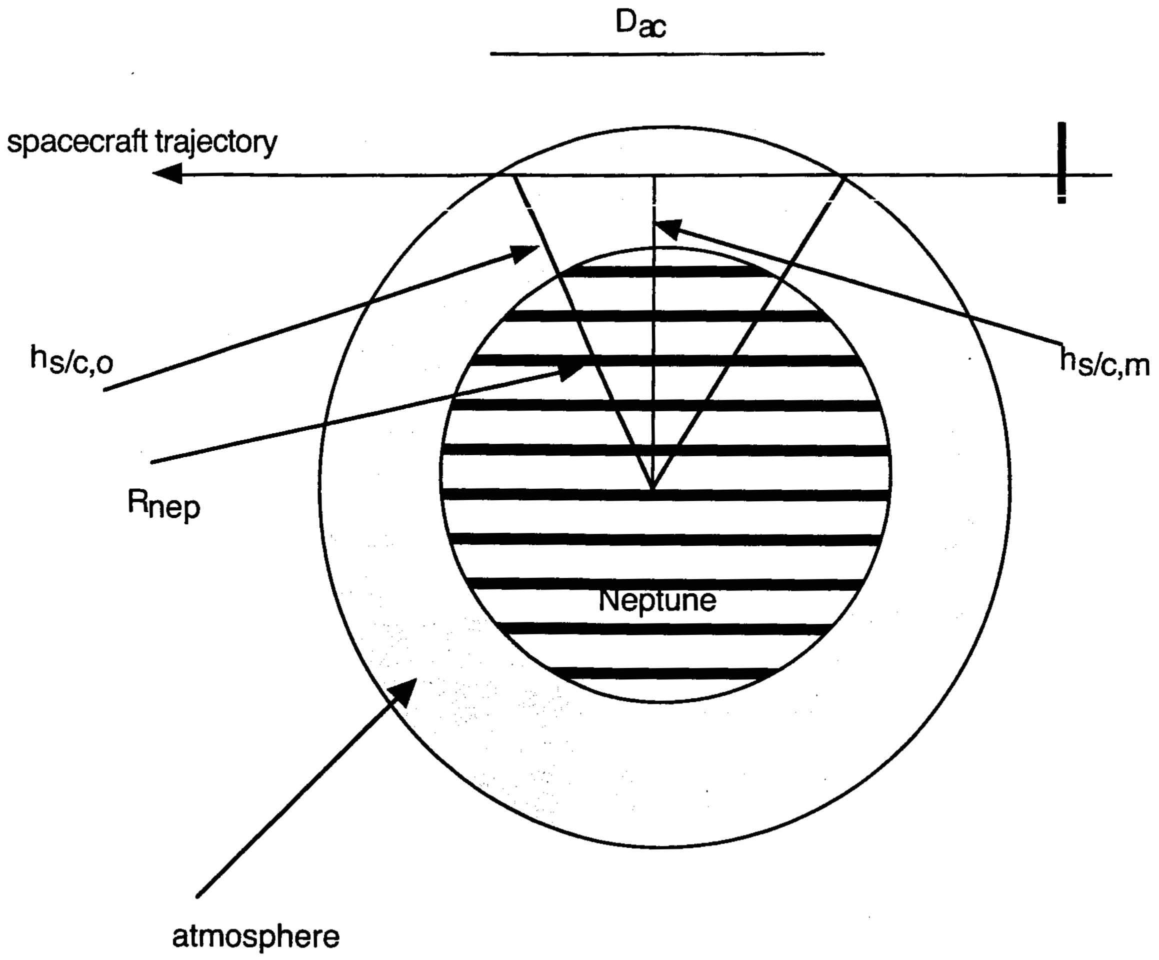


Fig. A.13. The Oort Cloud Explorer